Hydrodynamic field study of a shallow estuarine subembayment, Sherman Lake, California

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Abstract

Sherman Lake, California, has two hydrodynamically distinct regions: a tidally forced jet located along the eastern flank that creates an important hydraulic connection between the Sacramento and San Joaquin Rivers, and a relatively quiescent area in the west. The forcing mechanisms driving circulation and transport are spatially variable in Sherman Lake, a characteristic, we are finding, that is typical of shallow-water environments in the San Francisco Bay and Delta. As interest in restoring and creating tidal wetlands and other shallow-water environments in the Delta increases (CALFED, 2001), serious consideration of the heterogeneity of the physical environment must be taken when developing restoration objectives and monitoring programs.

Background

The Sacramento-San Joaquin Delta (Delta) is a complex network of more than 1150 kilometers (km) of tidally influenced channels and sloughs that is vital to the State of California's water delivery system (Figure 1). More than 20 million people depend on the Delta for drinking water; 1.8 million hectares (ha) of cropland are irrigated with Delta water; and several native threatened or endangered fish species reside in or migrate through the Delta.

Two strong forcing mechanisms drive circulation, transport, and mixing in the Delta: 1) riverine input from the north, south, and east; and 2) tides propagating from the Pacific Ocean through San Francisco Bay from the west. Runoff enters the Central Valley watershed primarily from the Sierra Nevada Mountains to the east and is conveyed into the Delta by the Sacramento River from the north, the San Joaquin River from the south, and streams from the east including the Mokelumne and Cosumnes Rivers. During water year 1998, the Sacramento River contributed 78 percent, the San Joaquin River contributed 18 percent, and the east-side streams contributed the remaining 4 percent of the total flow
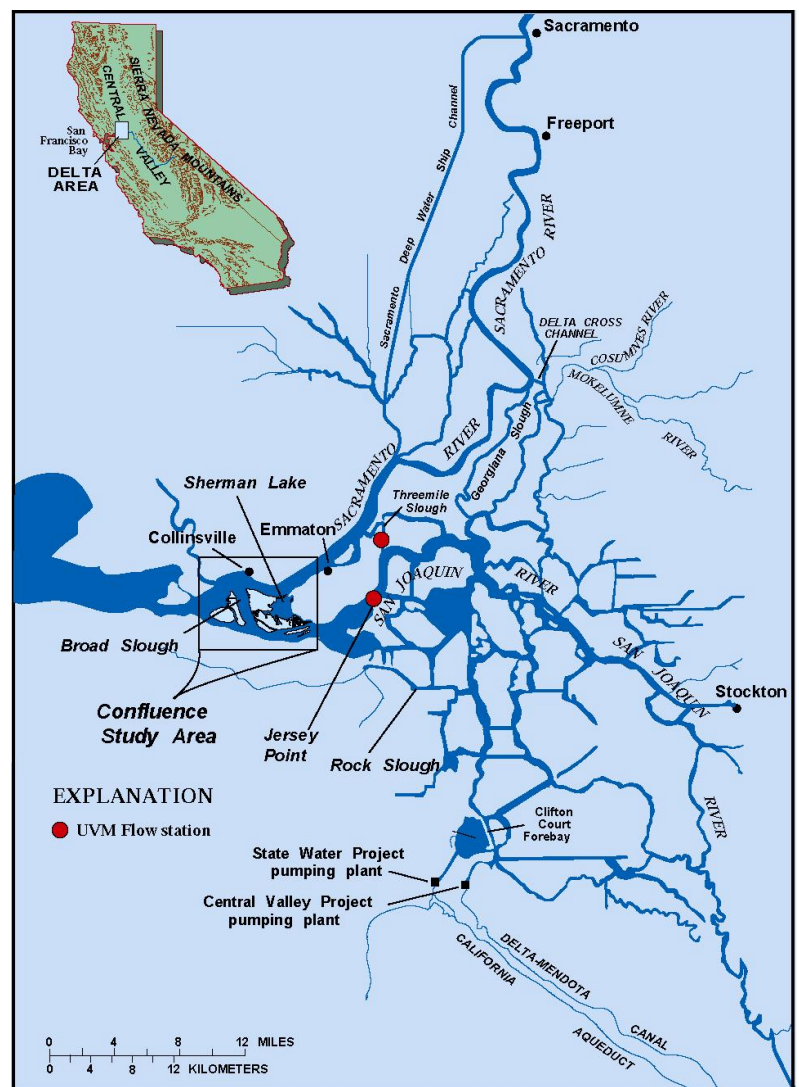

Figure 1: Map of Sacramento – San Joaquin Delta, California.

entering the Delta (DAYFLOW, 1978). Tidal forcing from the Pacific Ocean causes twice-daily water level variations on the order of 1 meter (m) and currents on the order of 50 centimeters per second (cm/s) in the western Delta (Figure 2). This strong tidal forcing causes mixing between the waters of riverine and oceanic origin (Paulsen, 1997) through shear flow dispersion and tidal pumping and trapping mechanisms (Fischer, *et.al.*, 1979).
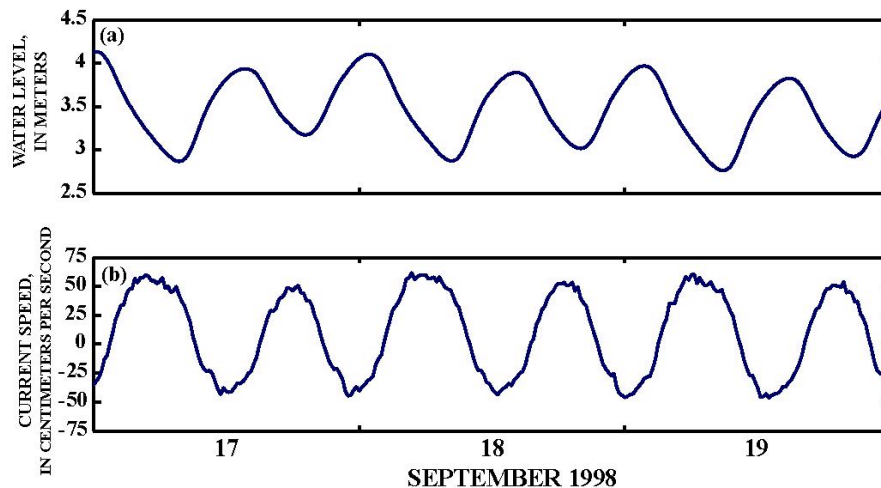

Figure 2: a) Stage on Sacramento River at Collinsville and b) current speed on Sacramento River at Sherman Lake "SAC".

Sherman Lake is located where water from the river systems and the coastal ocean mix, making the hydrodynamics of this region both complex and important. The mixing of waters in this region significantly affects the saltwater intrusion into the interior Delta. Ocean-derived salinities[1] in this region vary seasonally from zero, following the first large outflow event in the winter, to 12 during low-flow periods in the late-fall or early-winter. The increased salinity during low-flow periods is of particular concern due to water-quality standards that can constrain exports from the State and Federal Water Projects that pump water from the southern Delta (Figure 1). Water-quality standards must be met at Jersey Point on the San Joaquin River, and Emmaton on the Sacramento River, and drinking-water standards (< 250 milligrams chloride per liter water) must be met at the Contra Costa Water District pumping plant at Rock Slough (Figure 1, State Water Resources Control Board, 1995). The water quality standards, which regulate the extent of salinity intrusion into the Delta from the Bay, are met through a combination of increased reservoir releases and reductions in pumping.

Sherman Lake was created in 1969 when a subsided island used for irrigated agriculture was flooded by a levee failure. Today, Sherman Lake is connected to the Delta through a number of levee breaches, including two openings in the north that connect Sherman Lake to the Sacramento River, a small opening in the west that connects Sherman Lake to Broad Slough, and multiple openings in the south through Mayberry Slough, Mayberry Cut and Donlon Island that connect Sherman Lake to the San Joaquin River (Figure 3). Prior to this study, Sherman Lake was thought to be a quiescent area that made relatively minor contributions to the transport of water, water-quality constituents, and biota between the Sacramento and San Joaquin Rivers. Results from this study show that although western Sherman Lake exhibits "lake-like"

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[1] Salinity in this paper is expressed according to the Practical Salinity Scale, 1978 (UNESCO, 1978). The salinity of freshwater is zero and of the coastal ocean near San Francisco Bay is approximately 34.

characteristics, the eastern portion of the "lake" provides an important transport pathway between the Sacramento and San Joaquin Rivers.
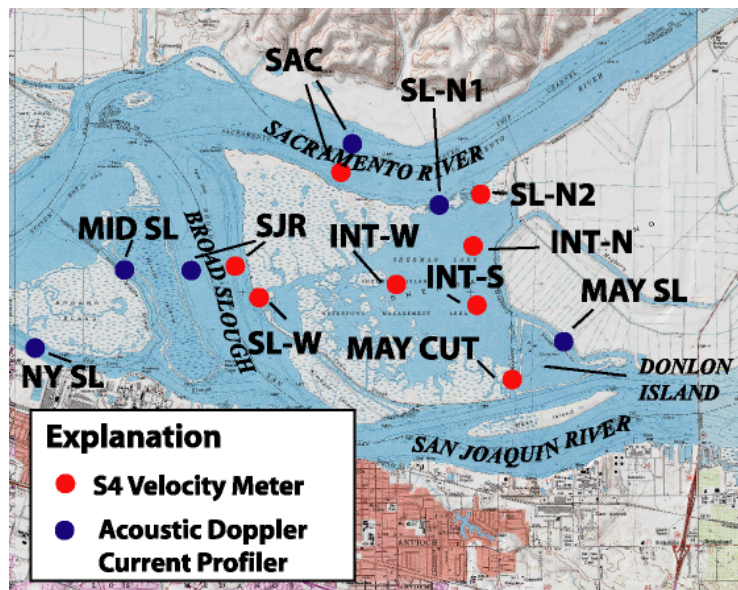

Figure 3: Study area and equipment location map.

Introduction

The objectives of this study were 1) to characterize an existing shallow-water environment in the Sacramento-San Joaquin Delta and 2) to provide validation and calibration data for modeling efforts.

There is significant interest in understanding the physics and biology of shallow-water environments in the San Francisco Bay and Delta system due to the massive restoration effort underway. During the next 3 decades, the creation of more than 4000 hectares (ha) of shallow-water habitat and 12,000-18,000 ha of emergent tidal wetlands is planned (CALFED, 2001). Understanding the physical processes of Sherman Lake, an existing shallow-water environment, is an important component to developing strategies for restoring other areas of the Bay and Delta system.

One-dimensional numerical modeling studies of the Delta by the California Department of Water Resources have shown that the predictions of the flows and salinity throughout the interior Delta are extremely sensitive to the characterization of Sherman Lake in the model. Despite the importance of this region, little data had been collected prior to 1998. Only water level and salinity data had been collected at a few locations near the confluence of the Sacramento and San Joaquin Rivers and no flow data had been collected. During the fall of 1998, the U.S. Geological Survey (USGS) conducted a 3-month study of the hydrodynamics of the confluence area, including Sherman Lake.

Methods

The exchange of water was measured in the vicinity of the confluence using a combination of an existing long-term flow network, deployed equipment, and surface drifters. A long-term network of nine ultrasonic velocity meter (UVM) stations measured index velocities and stage throughout the Delta every 15 minutes. Sixteen additional sampling stations were deployed from mid-September to late-November 1998 to study the hydrodynamics of Sherman Lake and the confluence of the Sacramento and San Joaquin Rivers. A combination of acoustic Doppler current profilers (ADCP) and magnetic velocity meters (S4) were used to measure

velocities, and Ocean Sensors OS200 probes were used to monitor conductivity, temperature, and depth. All of the long-term UVM stations and five of the short-term velocity stations were successfully flow-calibrated using a boat-mounted ADCP system (Simpson and Oltmann, 1993). To augment the Eulerian fixed-site sampling, drifters that move at the speed of the surface currents, were used to document the primary flows paths within Sherman Lake and to measure the tidal excursions in the area of the confluence.

This paper focuses on the exchange of water within and through Sherman Lake using stage, velocity, and discharge data collected from five of the short-term stations (SAC, SL-N1, MAY SL, INT-N, INT-W) (Figure 3) and two of the long-term stations (Threemile Slough, San Joaquin River at Jersey Point) (Figure 1).

Table 1: Summary of Deployed Equipment for 1998 Confluence Study (Station labels refer to Figure 1 and Figure 3). ADCP, acoustic Doppler current profiler; S4, magnetic current meter; UVM, ultrasonic velocity meter.

Station Label	Station Desciption	Equipment	Parameters	Notes
SL-N1	Northern Opening to Sherman Lake - #1	ADCP	Velocity, Flow, Stage	Station successfully flow rated
SAC	Sacramento River at Sherman Lake	ADCP S4	Velocity, Flow, Stage	Station successfully flow rated
MAY SL	Mayberry Slough	ADCP	Velocity, Flow, Stage	Station successfully flow rated
INT-N	Interior Sherman Lake - North	S4	Velocity, Stage	
INT-W	Interior Sherman Lake - West	S4	Velocity, Stage	
TMS	Threemile Slough at San Joaquin River	UVM	Flow, Stage	Long-term flow station
JPT	San Joaquin River at Jersey Point	UVM	Flow, Stage	Long-term flow station

Results

Transport in any water body is fundamentally Lagrangian. However, Lagrangian sampling using dye or drifters is extremely manpower-intensive, often making it cost prohibitive. Moreover, because Lagrangian particle trajectories in tidal estuaries depend strongly on the time of particle release within the tidal cycle (Cheng and Casulli, 1982), it is very difficult to study a full range of hydrologic conditions. Eulerian measurement techniques, such as the deployment of self-contained equipment that employ high frequency sampling strategies, allow the study of tidal to seasonal timescale variations. However, Eulerian sampling techniques cannot yield a complete picture of the spatial variability, particularly when the local tidal excursions are much greater than the physical dimensions of the study area. In the case of Sherman Lake, Eulerian measurements can be used to deduce the fluxes of water and water-quality constituents through its boundaries, but they cannot be used to determine where the water that moved through Sherman Lake ultimately traveled. In this study we relied heavily on Eulerian fixed-site sampling because
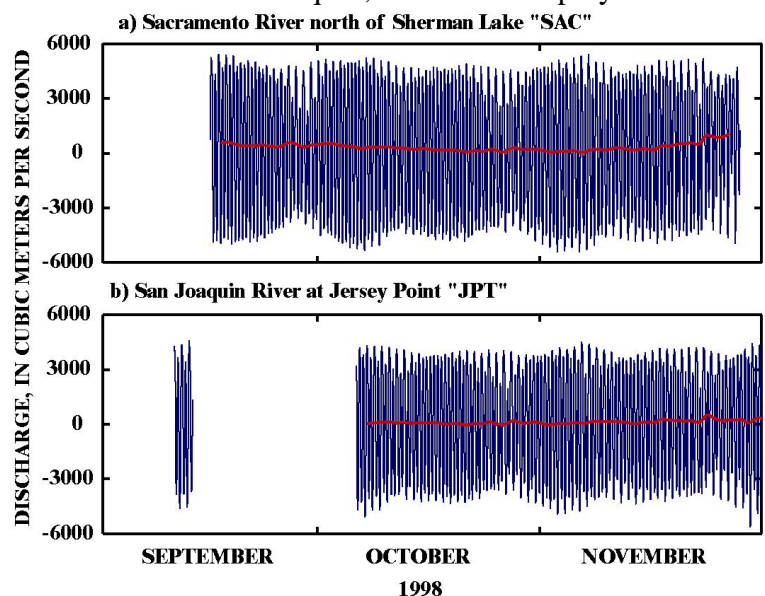

Figure 4: Tidal (blue) and net (red) flows in the a) Sacramento River and b) San Joaquin River near the confluence study area.

it requires less manpower. Some Lagrangian measurements were made to understand flow paths and tidal excursions.

Eulerian Transport

The network of fixed-station equipment is shown in Figure 3. This extensive network of equipment allows us to characterize transport through and within Sherman Lake. Each instrument recorded continuous data at a 10-minute interval. Net discharge was computed using a low-pass, fast Fourier transform digital filter with a stop frequency of 0.0333/hour (or a period of 30 hours) and a pass frequency of 0.025/hour (or a period of 40 hours).

Exchange through Sherman Lake

Tidal flows in the Sacramento and San Joaquin Rivers near the confluence were on the order of ±4,000 to ±5,500 cubic meters per second (m^3/s) (Figure 4), whereas the tidal flows through Threemile Slough and the northern opening of Sherman Lake were on the order of ±1,000 to ±1,200 m^3/s (Figure 5). Tidal flows through Mayberry Slough were on the order of ±400 m^3/s; however, this is only one of the southern connections between Sherman Lake and the San Joaquin River, and the total flows through all of the southern openings is likely on the order of what is seen in the north because very little exchange was observed through the western opening (Figure 7). Water flows from the north to the south through Sherman Lake during flood tides and reverses during ebb tides.
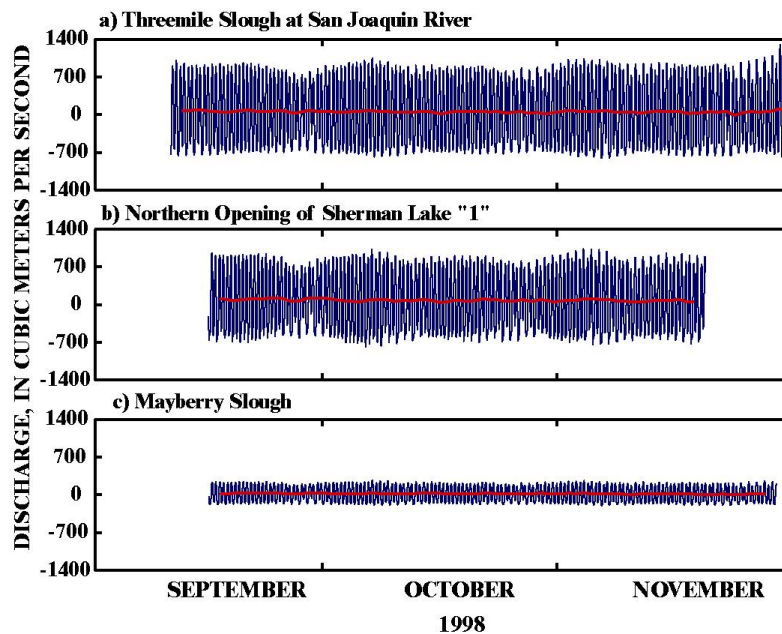

Figure 5: Tidal (blue) and net (red) flows in a) Threemile Slough, b) the
northern opening of Sherman Lake, and c) Mayberry Slough.

The net flows generally are higher on the Sacramento River than on the San Joaquin River or through Sherman Lake (Figure 6). In general, fluctuations in the net flows throughout the Delta are due to changes in upstream reservoir releases, water exports, runoff events, and atmospheric pressure. The data collected in the confluence area shows that the net flow is on the order of 85 m^3/s from the north to the south through Sherman Lake (Figure 5b, 6).

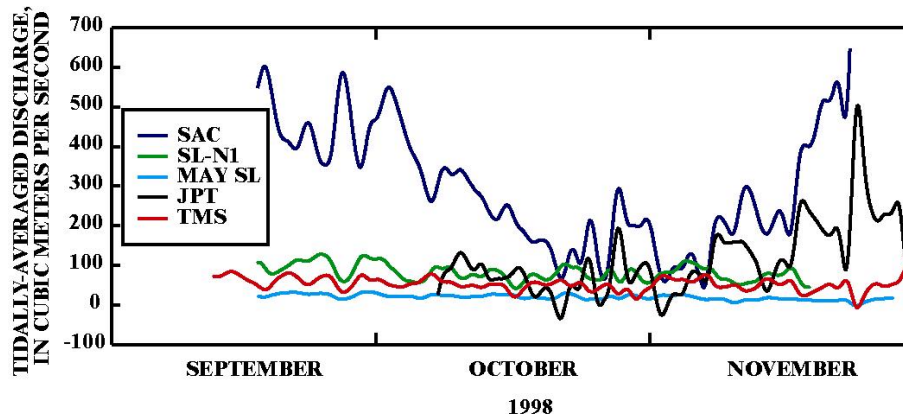**Figure 6: Net discharge at five stations in the confluence region. The station labels refer to Table 1.**

The measured net flow of 85 m³/s through Sherman Lake was higher than expected, because Sherman Lake was thought to be a relatively quiescent shallow-water habitat. This flow was on the order of the other major north-south connecting channels in the Delta. In addition to Sherman Lake, there are three other major channels connecting the Sacramento River and the San Joaquin River system: the Delta Cross Channel, Georgiana Slough and Threemile Slough. The Delta Cross Channel is man-made with operable radial gates that are manipulated to control the flows through the Cross Channel. The Delta Cross Channel conveys a net flow of 85–120 m³/s during normal, full-open, conditions. Georgiana Slough conveys net flow on the order of 60–85 m³/s during typical fall low-flow periods. Threemile Slough conveyed approximately 60 m³/s net flow during the period of this study. This study showed Sherman Lake is an important conveyance pathway carrying roughly 25% of the net flow between the two river systems.

Exchange within Sherman Lake

There are two hydrodynamically distinct regions in Sherman Lake. A strong north-south jet that connects the major openings and runs roughly parallel to the lake's eastern boundary and a relatively quiescent area in the west, where tidal forcing is weak and wind-driven circulations are more important (Figure 3).
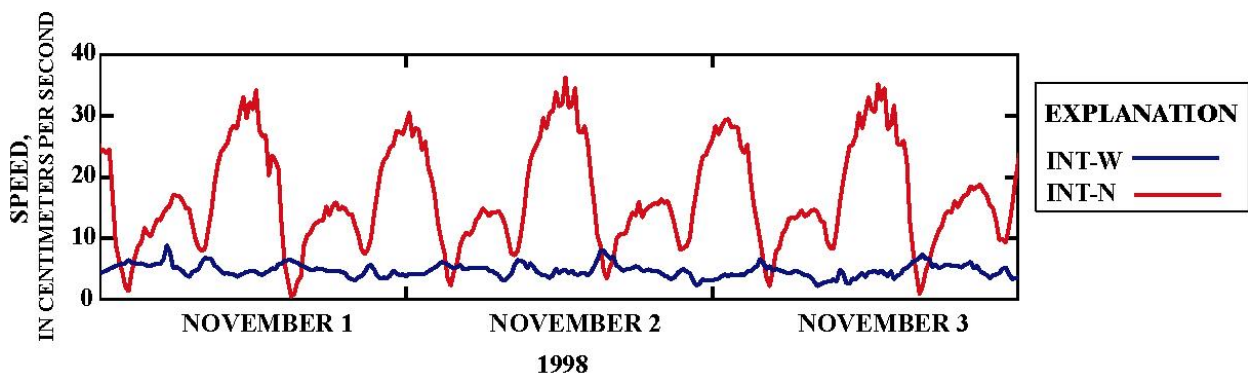

Figure 7 – Time series plots of the measured current speed in the interior of Sherman Lake: (red) INT-N, and (blue) INT-W. The peak tidal current speeds in the eastern part of the lake (INT-N) are on the order of 30 cm/s compared to the western part of the lake (INT-W) where the current speeds are relatively weak, on the order of 5 cm/s.

The currents in this jet are quite high given the shallow depths, peaking at approximately 30 cm/s (Figure 7). The flow in this relatively narrow jet accounts for most of the flow through Sherman Lake discussed above. In contrast, the western portion of Sherman Lake is relatively quiescent

with current speeds on the order of 5 cm/s or less. Interestingly, even though the tides strongly influence the north-south exchange through the openings, there is relatively little tidal signal in the western portion of the island, as measured at INT-W. This suggests that the hydrodynamics in the western portion of the lake resemble "lake-like" conditions characterized by longer residence times and water exchanges that are dominated by wind-driven circulations and diffusive mixing with the north-south jet.

Figure 8: Drifter paths on flood tide over 5 hours. Note that while several drifters were released together in the northern section of Sherman Island, they split near Donlon Island and followed different paths. One group of drifters made it through Mayberry Slough to the San Joaquin River and traveled a total of 10.3 km. The other group traveled through Mayberry Cut and did not enter the San Joaquin River, traveling a total of 3.2 km (Cuetara and Burau, 2000). High wind conditions caused this experiment to be terminated early.

Lagrangian Transport

The measured net flow from the Sacramento River to San Joaquin River through Sherman Lake was on the order of 85 m^3/s during the study period. Differences in the phase of tidal currents on the Sacramento and San Joaquin Rivers across Sherman Lake cause the net transport from the north to the south. The Lagrangian drifter studies were consistent with this transport. Drifters released at the beginning of a flood tide on the north side of Sherman Lake traveled 5.8 km farther than drifters released at the beginning of an ebb tide on the south side of Sherman Lake (compare Figures 8 and 9). Currents on the San Joaquin River side of Sherman Lake lag those on the Sacramento River side

by approximately 1 hour (Figure 10) and the drifters crossed Sherman Island in about the same period of time, 1 hour. Therefore, a drifter released into Sherman Lake from the Sacramento River at the beginning of flood tide traverses the lake in about 1 hour and reaches the San Joaquin River at approximately the same time that the flood tide begins on the San Joaquin River. The drifter then travels up the San Joaquin River during the entire flood tide (Figure 8). Conversely, a drifter released into Sherman Lake from the San Joaquin River at the
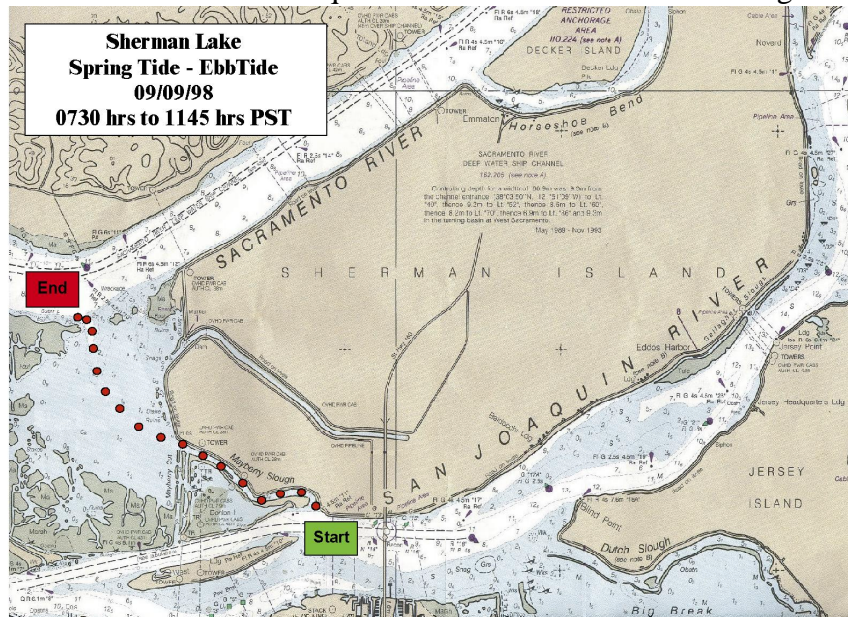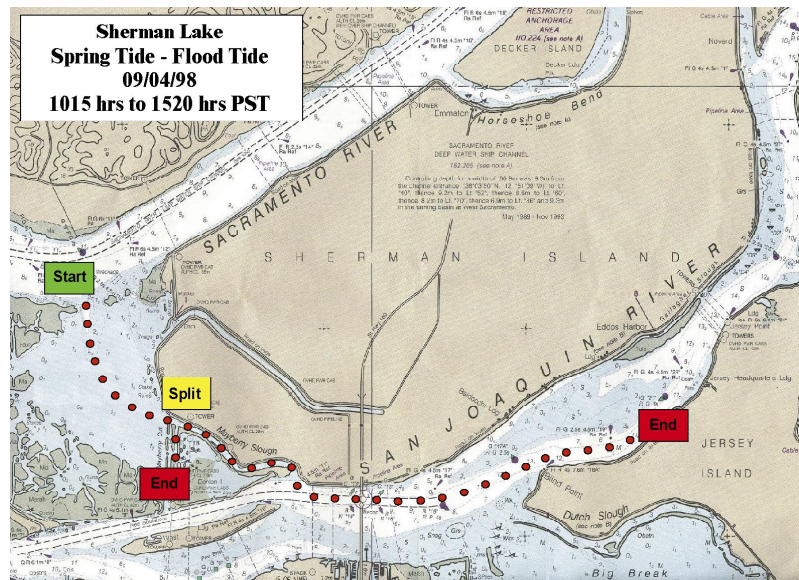
Figure 9: Drifter path on ebb tide over 4 hours. A group of drifters was released and the entire group traveled 4.5 km to the junction between Sherman Lake and the Sacramento River (Cuetara and Burau, 2000).

beginning of ebb tide traverses the lake in roughly 1 hour but reaches the Sacramento River approximately 2 hours into the ebb tide on the Sacramento River, and thus travels a shorter distance overall (Figure 9).

Comparison of the measured values collected at Sacramento River north of Sherman Lake (SAC) and the estimated values calculated for the San Joaquin River at the southern opening of Sherman Lake show that the gravity wave arrives at the northern opening to Sherman Lake approximately 1 hour before it arrives at the southern opening (Figure 10). No equipment was placed near the southern opening of Sherman Lake, so data from the San Joaquin River at Jersey Point (JPT) station was shifted 13 minutes, based on wave celerity, to estimate the tidal phase at the southern opening of Sherman Island:

$$\Delta t = \frac{\Delta x}{\sqrt{gh}}$$

where, Δt is the time it takes a gravity wave to travel a distance, Δx, between two locations (estimated at 7.3 km); and $\sqrt{gh}$ is the wave celerity, the speed of the gravity wave, g is gravity acceleration (9.81 meters per second squared) and h is the reach-averaged water depth (estimated at 8.5 m).
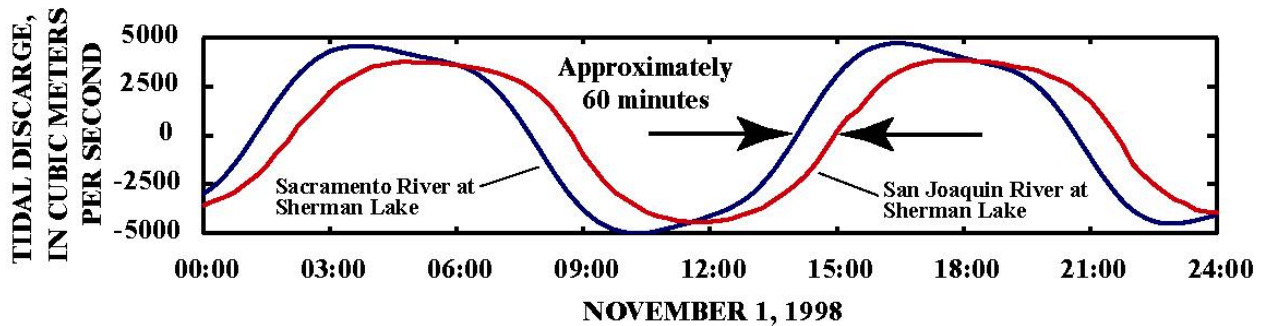

Figure 10: Tidal discharge at Sacramento River at Sherman Lake (blue), and San Joaquin River at Sherman Lake (red). The gravity wave arrives on the north side of Sherman Lake approximately 1 hour before it arrives on the south side of Sherman Lake.

This hour phase difference occurs for two reasons: (1) the distance the tides travel to the Sherman Lake openings is greater along the San Joaquin River than along the Sacramento River and (2) the reach-averaged water depth is less on the San Joaquin River and thus waves travel more slowly on the San Joaquin River. The difference between the flood and ebb drifter path lengths shown in Figures 8 and 9 is a clear demonstration of the process of "tidal pumping" discussed by Fischer (1972). Large quantities of water originating from the Sacramento River are effectively "pumped" to the San Joaquin River through Sherman Lake because of the difference between the phases in the tidal currents.

Conclusions

Analysis of field data show that Sherman Lake is comprised of two regions with very different hydrodynamic characteristics. Along its eastern flank, in a line connecting the north and south levee breaches, the currents are relatively strong (reaching 30 cm/s) for a shallow-water environment, creating an important hydraulic connection between the Sacramento and San Joaquin Rivers. This connection between the Sacramento and San Joaquin Rivers transports approximately 25 percent of the net flow between the Sacramento and San Joaquin Rivers. The tidal currents in the western portion of Sherman Lake are weak (< 5 cm/s), suggesting longer

residence times and circulation controlled to a greater degree by wind and other forcing mechanisms. Differential tide propagation creates water surface gradients that not only drive the strong flows through Sherman Lake but also cause large asymmetries between ebb and flood tidal excursions. Tidal asymmetries allow water to be transported effectively from the Sacramento River to the San Joaquin River.

This study shows that Sherman Lake is not a homogeneous environment. The forcing mechanisms driving circulation and transport are spatially variable within Sherman Lake. This finding is consistent with other major shallow-water studies that have been conducted within the Delta. As interest in restoring and creating tidal wetlands and other shallow-water environments in the Delta increases (CALFED, 2001), heterogeneity of the physical environment must be seriously considered when developing monitoring programs or restoration objectives.

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